

A Study on Spin Transport in Paramagnetic Insulators

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In this thesis, we explored spin transport in normal metal/paramagnetic insulator junctions. First, we demonstrated the long-range and efficient spin transport in gadolinium gallium garnet ($\text{Gd}_3\text{Ga}_5\text{O}_{12}$: GGG). We observed spin current propagation in paramagnetic GGG over several microns. Comparison between the experimental results and theoretical modeling clarifies that the spin conductivity of GGG is at low temperatures larger than that of YIG, supposedly the best material for spin transport. In the case of GGG, the strong dipole interaction forms spin-wave spin currents.

Next, we also investigated the spin Hall magnetoresistance (SMR) at a Pt/GGG interface. The observed magnetoresistance clarifies the mechanism of the interfacial spin transfer between conduction electron spins and localized paramagnetic spins. This thesis expands the material class of spintronics to paramagnetic insulators and open a new research field: *Paramagnetic spintronics*.

This thesis consists of 5 chapters, and the details are as follows.

- *Chapter 1* explains the concept of spin current and overview the spintronics phenomena.
- *Chapter 2* shows the properties of the materials used in this thesis, the fabrication process of the samples, and the measurement methods. We discuss the crystal structure and magnetism of GGG. We explain the detail of the nano-fabrication using a magnetron sputtering, *e*-beam lithography, photolithography, and Ar^+ milling technique.
- *Chapter 3* shows the observation of long-range spin transport through paramagnetic insulators.

We showed the long-range spin transport thorough paramagnetic GGG at low temperature and high magnetic field. Spin current in GGG can be electrically injected and detected using the spin Hall and inverse spin Hall effects in the attached Pt contacts. The observed signal depends linearly on the excitation current. When we change the temperature, the signal remains up to 100 K, which is much higher than the Curie-Weiss temperature. This suggests the observed signal cannot be attributed to the short-range spin correlation. On the other hand, at such condition, GGG acquires large field-induced magnetization, and thus the strong dipole interaction appears and can drive spin waves without an exchange stiffness. Comparison between our theory and experimental result clarifies the spin diffusion length and spin conductivity of GGG. The obtained spin conductivity is much greater than that of yttrium iron garnet, being attributed to the long-range nature of the dipole interaction, which supports spin waves in GGG.

- *Chapter 4* presents the results on the spin Hall magnetoresistance in a Pt/GGG junction system.

We investigated magnetoresistance in a Pt/GGG sample. The resistivity of Pt on GGG changes in response to the direction and amplitude of magnetic field. This suggests that the observed magnetoresistance is relevant to the field-induced magnetization, the paramagnetic SMR. Furthermore, we found the spin Hall anomalous Hall effect (SHAHE) signal in the conventional Hall measurement. We modeled the spin transport at the Pt/GGG interface based on the interfacial exchange interaction, and it clarifies the correlation between the SMR (SHAHE) and spin transfer (field) torque acting on the field-induced magnetization. Comparing the theory and experimental results, we found the values of the microscopic interfacial parameters, allowing us to extract spin conductances at the interface, the real and imaginary part of spin mixing conductance and longitudinal spin conductance. The estimated maximum values of three spin conductances at the Pt/GGG interface are in the same order of magnitude, highlighting the unique feature of the paramagnetic spin transport at the interface.

- *Chapter 5* summarize the results in this thesis and suggest the perspective.

This thesis shows key spintronic functions of paramagnetic insulators such as the injection/propagation/detection of spin currents. We expand the material class of spintronics to paramagnetic

insulator and open a new research field: *Paramagnetic spintronics*. The unique functions and advantages of paramagnets we explored in this thesis may attract much attention for applications, and thus we hope our thesis contributes to rapid progress in this area.

論文審査の結果の要旨

物質中のスピン角運動量の流れであるスピン流の生成及び利用は、スピントロニクス of 学理の重要な位置を占めてきた。スピン流を用いることで、ナノ領域での磁性制御や磁気情報の読み取りが可能になっており、情報デバイスやエネルギー変換素子への応用もはじまっている。スピン流のキャリアとしては、従来金属中の伝導電子や磁性体中のスピン波が使われてきた。本論文は、従来スピン流科学の対象と考えられてこなかった常磁性絶縁体中のスピン流物性を明らかにし、常磁性体中のスピン伝搬機構及び常磁性体/金属界面でのスピン交換機構を解明するものである。

強磁性体では、強い交換相互作用によってスピンに長距離秩序がもたらされ、スピン波スピン流はこの長距離秩序のダイナミクスによって運ばれている。長距離秩序のない常磁性体中には、スピン流を長距離にわたって流すことができないと考えられてきた。本論文はこの常識を覆し、典型的な常磁性絶縁体ガドリニウム・ガリウムガーネット (GGG) 結晶において、マイクロメートルスケールでのスピン流伝搬やスピン流誘起物性を見出し、常磁性体を用いたスピントロニクス物性分野の端緒をひらいたものである。まず、GGG 結晶中にスピンホール効果の強い白金ナノワイヤ対を電子線描画法及びリフトオフ法によって作製し、低温の非局所電気伝導を測定した。この信号の磁場方位及び温度依存性を測定し、この信号が GGG 中にスピンホール効果によって誘起されたスピン流の伝搬による逆スピンホール電圧であること、スピン流の緩和長がマイクロメートルスケールであり、スピン流伝導度は典型的スピン波スピン流伝導体として知られるイットリウム鉄ガーネットよりも優れていることを示した。これは、常磁性体における初めての長距離スピン伝搬現象である。さらに、拡散スピン流モデルによる理論計算と比較することにより、この電圧の発生が磁場によって分極したガドリニウムイオンの常磁性磁化が担うスピン流であることを示した。また、この白金ワイヤの低温磁気抵抗を測定することで、低温で大きな磁気抵抗を見出した。磁気抵抗は顕著な磁場方位依存性を示し、その解析から、白金中のスピン蓄積とガドリニウムイオンとの相互作用がもたらすスピンホール磁気抵抗効果が観測された磁気抵抗の起源であることを突き止めた。このデータを解析することにより、白金・GGG 界面のスピン交換過程のパラメータ群の全貌をはじめて明らかにした。

大柳洸一氏提出の論文は、常磁性絶縁体中のスピン伝導現象をはじめて見出し、その伝導機構、伝導電子とのスピン交換機構を明らかにし、スピントロニクスの諸現象が常磁性絶縁体に拡張された新しい学問分野を切り拓くものであり、学問的に高く評価される。

以上の内容は、提出者の大柳洸一氏が自立して研究活動を行うに必要な高度の研究能力と学識を有することを示している。したがって、大柳洸一氏提出の博士論文は、博士（理学）の学位論文として合格と認める。